Star Formation Histories of the Galactic Satellites

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Abstract: Late accretion models for formation of the Galactic halo require that many Galactic satellite galaxies have been cannibalised into the halo field. Comparison of the metallicity and age distribution function of stars in the surviving satellites with the apparently exclusively old stars in the field halo can constrain the importance of any such process. We have developed a new objective technique to determine star formation histories in dSph galaxies. We apply this technique to the surviving Galactic satellites, deducing an approximately uniform distribution of ages for the constituents, quite unlike the halo field stars. Thus, late accretion did not play a substantial part in Galactic halo formation.

1 Introduction

The bulk of the stellar populations in the Galactic halo field and globular cluster stars show a well-defined turn-off, at $B - V \sim 0.4$, implying that the vast majority of the stars are old. The fraction of stars which lie blueward of this well-defined turn-off, with metallicities similar to that of the present dSphs, was analysed by Unavane, Wyse, & Gilmore (1996; hereafter UWG96) to place limits on the importance of the recent accretion of stellar systems similar to the extant (surviving?) dwarf satellite galaxies. UWG96 showed that very few ($\sim$ 10 per cent) stars were found to be bluer (and by implication, younger) than the dominant turnoff limit, with the highest value found for the more metal-rich halo ([Fe/H]> -1.5). Direct comparison of this statistic with the colour distribution of the turnoff stars in the Carina dwarf allowed UWG96 to derive an upper limit on the number of mergers of such satellite galaxies into the halo of the Milky Way. This upper limit was $\sim$ 60 Carina-like galaxies. The higher metallicity data constrain satellite galaxies like the Fornax dwarf; only $\sim$ 6 of these could have been accreted within the last $\sim$ 10 Gyr. No galaxy like either Magellanic Cloud can ever have merged. Interestingly, a limit of zero also applies to the Sagittarius dwarf galaxy (Ibata, Gilmore & Irwin 1995) if recent suggestions that it has a substantial membership of near-solar metallicity are correct.

   This result has recently developed even more general significance, with comparison of the evolution in the halo formation rate in model galaxies, calculated ab initio from hierarchical

structure formation models, with the observed evolution in the global star formation history indicating that the latter is not inconsistent with being largely driven by halo mergers at $z > 1$. Thus one would like to be confident that the Milky Way Galaxy really has not suffered such mergers, before concluding that the single good test case appears not to match the single available good model.

The question arises from the UWG96 analysis as to the validity of adopting Carina as a 'representative' dSph galaxy. Ideally, of course one would also like to consider the age distribution function of the dSph and the field halo stellar populations, rather than merely the colour data. Motivated by this, and the many other scientific applications of the method, Hernandez, Valls-Gabaud & Gilmore (1999; henceforth HVGG), and see also Gilmore, Hernandez, & Valls-Gabaud (1999), developed an objective technique to derive star formation histories. Application of this method to the set of dSph galaxies provides an objective determination of the age distribution in the dSph stellar populations, for comparison with the field halo (old) ages. This comparison has been achieved by Hernandez, Gilmore & Valls-Gabaud (1999, henceforth HGVG). HGVG used their reduction of archive HST observations of the resolved populations of a sample of dSph galaxies (Carina, LeoI, LeoII, Ursa Minor and Draco) uniformly taken and reduced, to recover the star formation histories (henceforth $SFR(t)$) of each, applying their new non-parametric maximum likelihood variational calculus method.

2 Objective Determination of Star Formation Histories

A detailed description of our new method for objective determination of star formation histories, which uses a variational calculus approach supplemented by maximum likelihood statistical analysis, is provided in HVGG. That reference also describes the extensive numerical tests carried out to ensure numerical reliability in the implementation. We provide just a short summary here.

The available and necessary information is an observed colour-magnitude diagram, extending below the main-sequence turnoff of the oldest population of interest, an independent determination of the stellar metallicities, and a set of model isochrones. Given all that, we can construct the probability that the n observed stars resulted from a certain star formation history, $SFR(t)$. This will be given by:

$$\mathcal{L} = \prod_{i=1}^{n} \left(\int_{t_0}^{t_1} SFR(t)G_i(t)dt \right), \tag{1}$$

where

$$G_i(t) = \frac{\rho(l_i;t)}{\sqrt{2\pi}\sigma(l_i)} exp \left(\frac{-\left[C(l_i;t) - c_i\right]^2}{2\sigma^2(l_i)} \right)$$

In the above expression $\rho(l_i;t)$ is the density of points along the isochrone of age t, around the luminosity of star i, and is determined by an assumed IMF (the results are not sensitive to this) together with the duration of the differential phase around the luminosity of star i. t_0 and t_1 are a maximum and a minimum time needed to be considered, for example 0 and 15 Gyr. $\sigma(l_i)$ is the amplitude of the observational errors in the colour of the stars, which are a function of the luminosity of the stars. This function is supplied by the particular observational sample one is analysing. Finally, $C(l_i;t)$ is the colour the observed star would actually have if it had formed at time t. HVGG refer to $G_i(t)$ as the likelihood matrix, since each element represents the probability that a given star, i, was actually formed at time t. Since the colour of a star having a given luminosity and age can sometimes be multi-valued function, in practice

we check along a given isochrone, to find all possible masses a given observed star might have as a function of time, and add all contributions (mostly 1, sometimes 2 and occasionally 3) in the same $G_i(t)$. In this construction we are only considering observational errors in the colour, and not in the luminosity of the stars. Although the generalisation to a two dimensional error ellipsoid is trivial, the observational errors in colour dominate to the extent of making this refinement unnecessary.

The condition that $\mathcal{L}(SFR)$ has an extremal can be written as

$$\delta\mathcal{L}(SFR) = 0,$$

and a variational calculus treatment of the problem applied. This in effect transforms the problem from one of searching for a function which maximizes a product of integrals to one of solving an integro-differential equation. The numerical implementation required to ensure convergence to the maximum likelihood SFR(t) is described fully in HVGG, as are the extensive tests and simulations using synthetic HR diagrams.

The main advantages of our method over other maximum likelihood schemes are the totally non-parametric approach the variational calculus treatment allows, and the efficient computational procedure. No time consuming repeated comparisons between synthetic and observational CMDs are necessary, as the optimal star formation history, independent of any preconceptions or assumptions, is solved for directly.

3   Star Formation Histories of the dSph satellites

Application of the variational calculus method to archival HST data for five representative dSph galaxies has been completed by HGVG, where further details may be found. The star formation histories of these five galaxies cover all possible combinations. Stars in UMi are exclusively old, with the star formation history of that galaxy resembling that of a metal-poor Galactic globular cluster. At the other extreme, LeoI shows continuing star formation over all times, rising to a gentle maximum about 3 Gyr ago. Carina illustrates a more constant rate of star formation, though again continuing over the whole history of the Local Group. Its use as a template for the mean star formation history is indeed justified. The CMD and derived star formation history for Carina is shown below (Figure 1), to illustrate the results and their diversity.

A special feature of the method we have developed and applied here is that the derived star formation rate has real units, most conveniently in solar masses per Myr, integrated over the whole dSph galaxy. Thus it is straightorward to sum the independent star formation histories, to provide a real history of the dSph galaxy system. This is the star formation history of the metal-poor outer halo. The result is shown in Figure 2.

It is worth noting that the decline of star formation to zero recently is an artefact of definition. Those satellite galaxies which are still forming stars today are not dSph, but are Irregulars, notably the LMC and SMC. Both of course are also quite metal rich, and are very large, compared to the metal-poor galaxies of relevance here. The rather massive Sgr dSph is also missing from this study, since inadequate photometric and abundance data exist as yet.
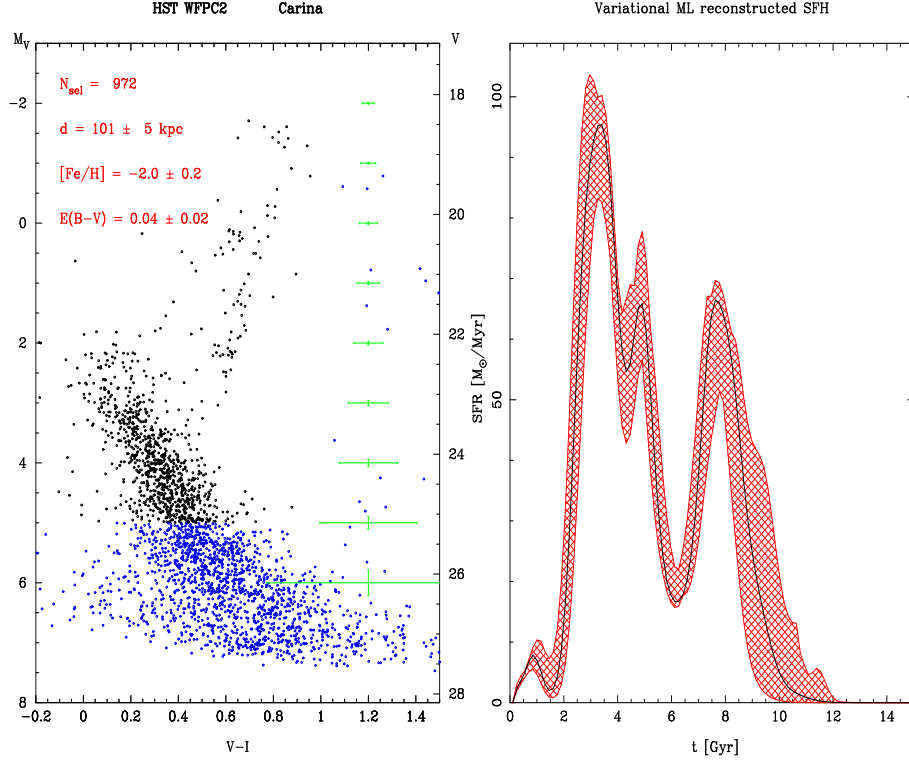
Figure 1: The HST colour-magnitude data (LHS) and corresponding star formation history (RHS) for the Carina dSph galaxy (HGVG). This figure illustrates the long duration of star formation in this dSph galaxy, an evolutionary history which is quite unlike that of field stars in the Galactic halo.
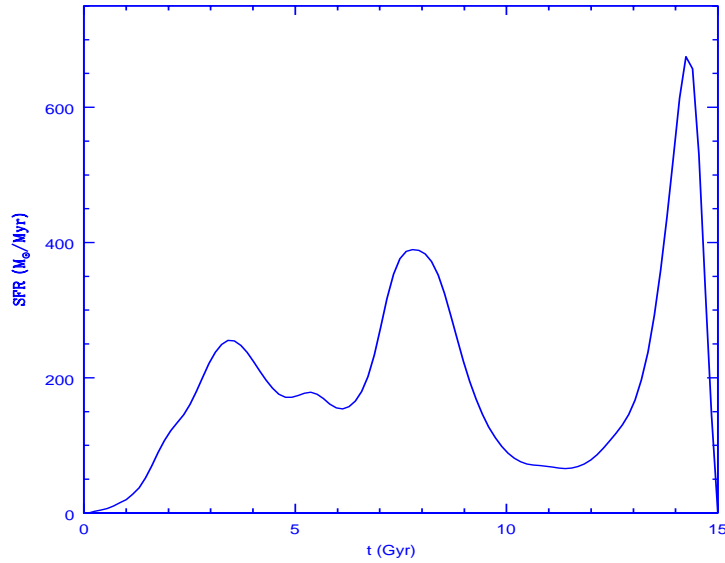

Figure 2: The integrated star formation history for the five dSph galaxies studied by HGVG. The 'mean star' in a dSph satellite galaxy is apparently of intermediate age.

4   Conclusions

We have developed a new methodology, which removes the guesswork from derivation of star formation histories corresponding to a given colour-magnitude diagram. Application of this method to HST data for five representative dSph satellite galaxies provides the star formation history of the metal-poor Galactic satellite system. This age distribution can then be directly compared with the equivalent distribution for Galactic halo field stars, and globular clusters. The Galactic field stars are, to better than 90% accuracy, all old. Thus, late Galactic mergers can have formed no more than some 10% of the field halo in the last $\sim$ 10 Gyr. This conclusion is profoundly at variance with standard galaxy formation models, which predict early star formation in dwarfs, which later merge to form Milky Way-sixed spirals. Either the dwarfs merged before they formed stars, or they never formed.

References

Gilmore, G., Hernandez, X, & Valls-Gabaud, D. 1999, in: Astrophysical Dynamics, eds D. Berry, D. Breitschwerdt, A. da Costa, & J. Dyson, ApSpSci special conference issue, in press

Hernandez, X, Gilmore, G., & Valls-Gabaud, D., 1999, MNRAS in press (HGVG)

Hernandez, X, Valls-Gabaud, D. & Gilmore, G., 1999, MNRAS 304, 705 (HVGG)

Ibata, R., Gilmore, G., & Irwin, M., 1995 MNRAS 277, 781

Unavane, M., Wyse, R.F.G., & Gilmore, G., 1996, MNRAS 278, 727